Fuzzy Identification and Predictive Control of the Alcoholic Fermentation Process

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Abstract **— In this work a fuzzy identification model for yeast growth applied to the specific case of alcoholic fermentation is presented. Two fuzzy techniques were applied, namely the designated Mamdani modelling and the TSK (Takagi Sugeno Kang) modelling. The results were compared with the ones obtained with a deterministic model proposed by Boulton. A predictive controller is also presented and the results obtained compared with the usual PID controller. The obtained results for the identification models and for the controller showed that both methodologies can be applied to biological processes.**

1. Introduction

Generally, biological processes are difficult to model. This is mainly due to the nature of the process, which leads to a large number of parameters needed to describe its dynamics when deterministic methods are used. Besides these type of models do not always allow to include all kind of information. First, because it is not simple to accomplish it and secondly because when we are able to do it, the model complexity is significantly increased and consequently the computational effort needed.

There are several works that present models for the fermentation process [1]. They can be more or less complex depending on the process variables used in the description. In 1980, Boulton [2], presented a model for the fermentation process that describes the yeast growth behavior as the result of the influence of substrate concentrations and the thermal effects resulting from the fermentation. This model is still accepted as a reference for the wine fermentation process and was used in this work as a comparative basis to validate the fuzzy models obtained.

Fuzzy modeling represents a simple and easy way for describing input-output relations. The fact that relationships are described in the form of rules of the type IF-THEN allows the designer to create simple models for linear and non-linear processes. In this last case, fuzzy logic has a great relevance since it allows to approximate non-linear systems by creating a rule base adapted to each functioning region. This is the case of the fermentation process, which like most of the biological processes is non-linear and difficult to describe by deterministic methods.

In this work a fuzzy identification model for yeast growth applied to the specific case of alcoholic fermentation is presented. Two fuzzy techniques were applied, namely the designated Mamdani modelling and the TSK (Takagi Sugeno Kang) modelling. The results were compared with the ones obtained with the model proposed by Boulton, which is commonly accepted by the scientific community as a reference model. Both Mamdani and TSK models were able to describe with accuracy the fermentation process.

Model based predictive control techniques are largely used in the petro-chemistry industries and are responsible for improving the process dynamics and for increasing the profits by reducing the associated control costs [3]. In fact, model based control permits the designers to predict the process dynamics and to determine the optimal control actions so the process can evolve according to the desired trajectories [4]. However, it is not common to see the use of model based predictive control techniques applied to biological processes. In this work a predictive controller for the alcoholic fermentation process is suggested and compared with a typical PID. This work is organized as follows: firstly, in section 2 the deterministic model proposed by Boulton is presnted followed by the Mamdani and TSK fuzzy models on section 3. Next a description of the predictive controller implemented is made and the results compared with a PID. Finally the main conclusions are presented.

2. The Boulton Model

The fermentation rate is determined by the sugar (glucose and fructose) transference rate to the yeasts [2]. This rate depends also on the yeast population in the must and is influenced by the temperature. This means that the medium variation temperature and the heat removal rate must be considered when modeling this kind of processes [2]. On the other hand, the temperature is affected by physical factors related with the reactor size and shape and with thermal properties of the refrigeration liquid [2].

Considering these factors, Boulton developed a model describing the alcoholic fermentation process. Although it is not very recent (obtained in 1977) it is still accepted as one of the most complete models regarding the fermentation process [1].

The referred model is presented as a set of equations representing six major aspects of the process, namely:

1 – Yeast growth and sugar utilization;

2 – Inhibition aspects of the substrate and product;

3 – Product formation (ethanol);

4 – Heat transfer effects;

5 – Temperature effects;

6 – Yeast viability;

These aspects are described by the following set of equations:

$$\frac{dX}{dt} = \mu X_v \tag{1}$$

where X represents the total yeasts mass and μ the specific yeast growth. X_v is the viable yeast mass.

$$\frac{dS}{dt} = -\left[\frac{\mu X_v}{Y_m} + mX_v \right] \tag{2}$$

where S is the sugar concentration, Y_m is a growing factor and m is the maintenance factor.

$$X_v = \alpha(t) X \tag{3}$$

where $\alpha(t)$ is a time function reflecting the age degradation.

$$\mu = \mu_m \frac{S}{K_S + S} e^{-K_E E} \tag{4}$$

where μ_m is the maximum specific growth, K_S is the saturation constant due to sugar, K_p is the inhibition constant due to the product and E is the product concentration (Ethanol).

$$\frac{dE}{dt} = -\alpha_R \frac{92}{180} \frac{dS}{dt} \quad with\ \alpha_R \le 0.95 \tag{5}$$

The last equation describes the product variation which depends on the substrate degradation. The α_R parameter represents the ideal yield factor of the fermentation reaction.

The heat generation rate is represented by equation (6). It depends on sugar consumption and on the released heat, ΔH.

$$\frac{dH}{dt} = \Delta H \frac{dS}{dt} \tag{6}$$

The temperature variation is described on equation (7). There are two major terms. The first one reflects the generated heat and the second one the released heat. ρ is the must density C_p is the thermal capacity of the medium, U is the thermal transference coefficient of the reactor and A is the area. T represents the temperature of the must and T_c the temperature of the refrigeration medium.

$$\frac{dT}{dt} = \frac{\Delta H}{\rho C_p} \frac{dS}{dt} - \frac{UA}{\rho C_p V} \left(T - T_c \right) \tag{7}$$

Other authors present in their works some of the values of the model constants [5], [6], [7] [8].

3. The Fuzzy Models

Based on the Boulton model 200 simulations with different initial conditions were performed. A sampling period of 6 samples per hour was used. The data obtained from the Boulton model sampling was used to train two fuzzy models. The first model was obtained using the Mamdani fuzzy structure and the second using the Takagi-Sugeno Kang (TSK) structure. Both models were built to identify the yeast growth.

The Mamdani fuzzy models describe the system relations by rules of the type:

$$R_i : IF\ \mathrm{x}\ is\ A_i\ THEN\ \mathrm{y}\ is\ B_i \tag{8}$$

In this case both antecedents and consequents of the rule are defined by fuzzy sets.

In the TSK structure the consequent is altered and instead of a fuzzy set it is defined by a function that is a combination of the antecedents:

$$R_i : IF\ \mathbf{x}\ is\ A_i\ THEN\ y_i = f_i(\mathbf{x}) \tag{9}$$

Because both structures are well described in the literature a more detailed description of them will not be presented here [9] [10].

Subsequently, the two obtained models were tested with data different from the training phase and the results were compared to the solution of the Boulton model. The results are presented in Figures 1 and 2.

The TSK model proves to result better for yeast growth modeling than the Mamdani model. Although the Mamdani model has a worst behavior than the TSK model the results presented here aren't the best ones. Better results were obtained with different test data. However to highlight the differences between those two models we choose to present an experiment where identification differences are significant.

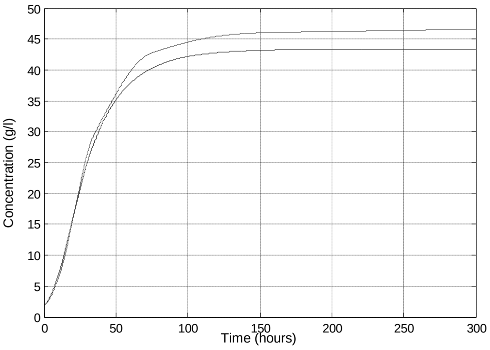

Fig. 1 – Mamdani fuzzy model (upper curve) and Boulton model for yeast growth (lower curve).

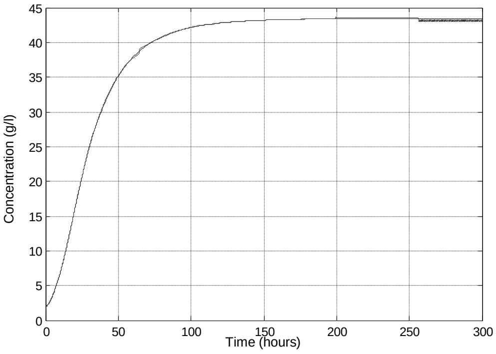

Fig. 2 - TSK fuzzy model (upper curve) and Boulton model for yeast growth (lower curve).

So we can conclude that TSK yeast growth model is able to describe with accuracy the fermentation process, with the advantage that fuzzy models are simpler, easier to implement and its structure is based on a base of fuzzy rules and inference process that can be easily understood by a human operator.

4. The Predictive Controller

In general a predictive controller is implemented using the following algorithm:

1- At each instant k predict the future system outputs, $y(k+j|k)$ with $j=1,\ldots,N$ for the prediction horizon N. The output values depends on the system values known until this instant and on the future control actions, $u(k+j|k)$, $j=0,\ldots,N-1$ that will be applied to the system. The predictions will be made using the system model.

2- The future control signals are obtained by minimizing an objective function trough an optimization process. The objective function consists, generally, on a quadratic error function.

3- At instant k send the control action $u(k|k)$ to the process. The new system output is then used to make new predictions for the system evolution (at instant $k+1$) and the new control signals. To do this, step 1 is repeated.

Note that control efficiency is highly dependable on the predictive model. If the plant model doesn't correctly describe the process evolution then predictions are wrong and, consequently, the control actions obtained incorrect.

Using the described algorithm the optimal control actions for a 25 steps were obtained. With these and with the help of a cubic interpolator a control law was built. The results obtained with this controller are shown in Figure 3.

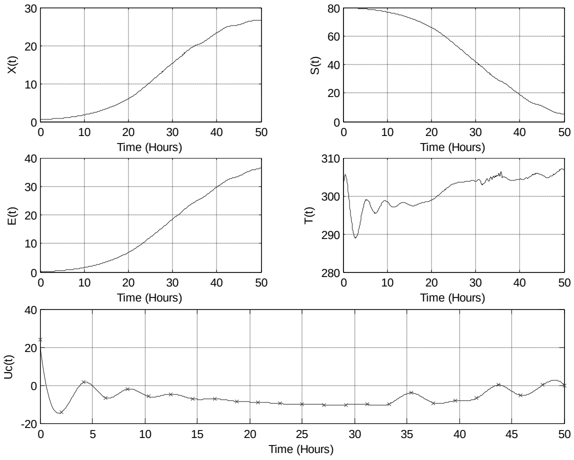

Fig. 3 – Results obtained with the predictive controller implemented.

The figure shows five curves. *X(t)* represents the yeast growth evolution, *S(t)* the sugar evolution, *E(t)* the ethanol concentration, *T(t)* the temperature evolution and *U(t)* the control effort.

In figure 4 the results of a PID controller for the same simulation are presented.

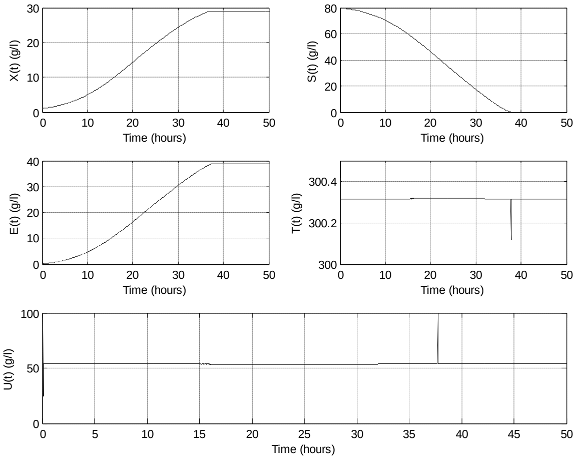

Fig. 4 – Results obtained with the PID controller implemented.

The results obtained for the PID controller are quite better than the ones obtained with the predictive controller. One can observe that with the PID controller the maximum ethanol concentration is achieved in a short period of time when compared with the predictive controller. However this is achieved with a bigger control effort.

5. Conclusions

This work comprehended two different parts. The first consisted in obtaining the yeast growth identification model for wine fermentation and the second one the development of a predictive controller that improves the necessary time to achieve the maximum ethanol concentration by adjusting the temperature.

In what concerns to the fuzzy identification models we can conclude that the TSK model obtained was able to describe with accuracy the fermentation process. In what concerns to the developed controller we can conclude that although it takes more time to achieve maximum ethanol concentrations the associated cost is significantly lower.

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